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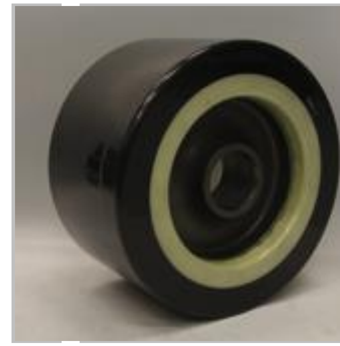

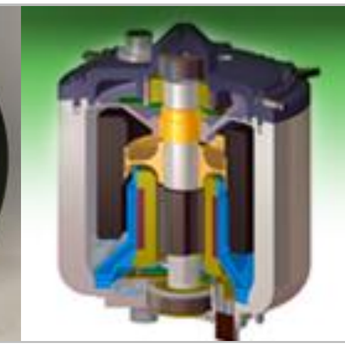

Nanofillers for Improved Flywheel Materials

September 2016

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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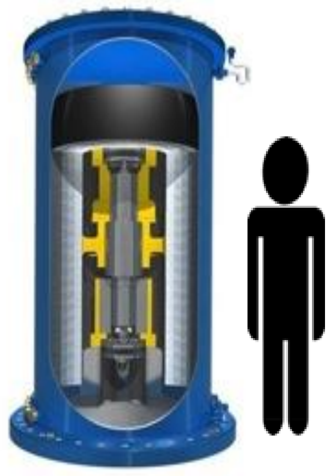
Project: Improved Flywheel Materials

Problem: Flywheels used to level the AC grid need to spin faster, which requires stronger rims. Focused on the material (C-fiber, glass fiber, resin) properties of composite flywheels.

No major changes to basic design, processing parameters, and/or cost can be incurred.



Goal: improve the overall strength of composite flywheel materials, so they can spin faster. Incorporate Sandia generated nano-filled materials into a commercial flywheel product and identify if there has been an improvement in the flywheel's performance

Approach: explore utility of nanomaterials in strengthening composite flywheel rims to improve performance. Low load levels (>5%) of nanoparticle fillers have led to dramatic property changes. Team with Cobham to produce Powerthru's existing commercial flywheel

Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

$$E_k = ½ \bullet I \bullet \omega^2$$

ω = angular velocity, I = moment of inertia of the mass about the center of rotation

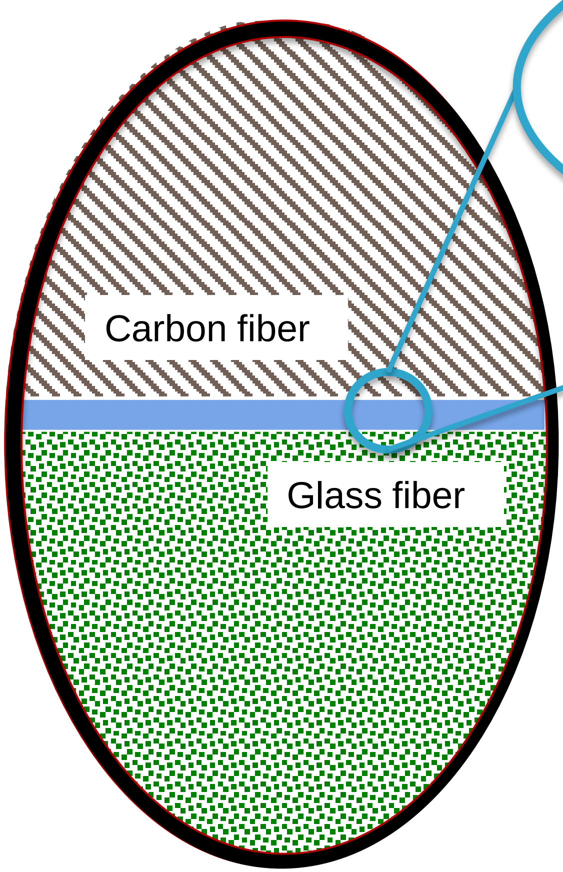
The amount of energy that can be stored is dependent on:

$$s_t = \rho \cdot r^2 \cdot \omega^2$$

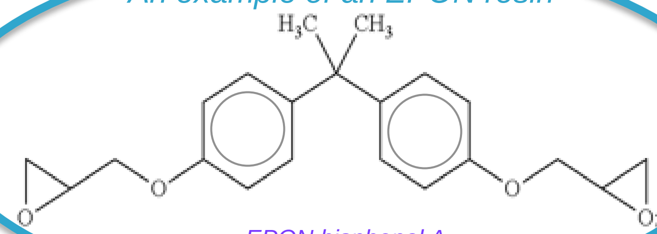
s_t = tensile stress on the rim, ρ = density, r is the radius, ω is the angular velocity of the cylinder.

Energy Storage Impact: The economics of flywheel-based energy storage can potentially be improved by a factor of 3 or more. The increased storage/supply is necessary to meet expected future complications expected as alternative energies (i.e., solar, wind, etc.) are introduced.

Approach to improve the composite flywheel materials properties.

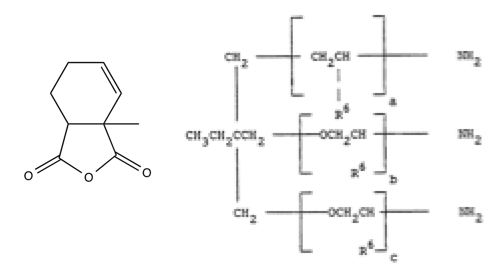


An example of an EPON resin



EPON bisphenol A

LS81k *Poly(oxypropylene) triamine*



An activator or crosslinker required to polymerize

Ceramic and Graphene Nanofillers

+ Fillers are a simple cost-effective method to alter resin properties.
+ Meso-sized fillers require high loads (> 60%) due to small surface area.
+ Nanomaterials are 2 D fillers with all surface area; added at low levels.
+ Surface functionality of the nanofiller can interact with the reactive epoxide group of resin.
+ Reactivity can be tailored by surfactant on the nanomaterial
+ Previous results indicate that wires and planes have biggest impact at lowest load level.

Loading (wt %):	4	$Al_2Si_2O_5(OH)_4$:	*23%*	*storage, 113% flexural strength,*
	3	Al_2O_3:	*75%*	*tensile strength,*
	2	SiO_2:	*3%*	*hardness, 57% impact, 65 % flex, 88 % tensile strength,*
	2	ZrP:	*52%*	*Young's Modulus, 14% tensile strength 6 %, fracture toughness,*
	0.4% CNT-2%	ZrP:	*41%*	*Young's Modulus, 55% tensile strength.*

Overall Objectives: Defining functionalized nanoparticle fillers effects on the ‘state-of-the-art’ working flywheel system.

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Team determined approach and tasks assigned based on expertise

Composite System

Resin/Epoxy System

Ceramic Nanomaterials

Surface Characterization

TiO_2 /graphene nanomaterials

Optimized Functionalized Nanofiller /Epoxy Characterization

Sample Production Evaluation

Test Specimen Functionalized Nanofiller Characterization

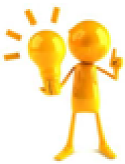
+ Increasing transverse strength is the pressing issue.

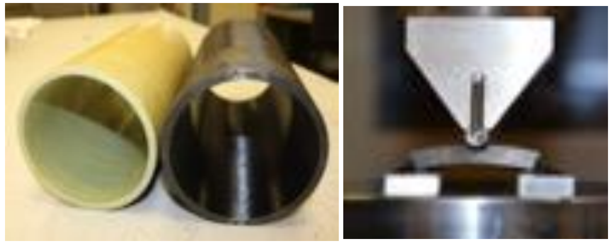
**** Incorporation of suggested nanomaterials or resins will represent verification of our approach***

TA filed

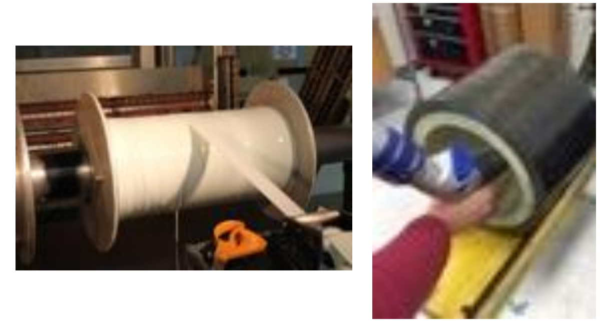
FY15 Flywheel Production

Timeline of program





30 % increase in sample strength



Nano-filled flywheel built

Project initiated

TRL 0

TRL 3

TRL 5

TRL 7/8

2010

2011

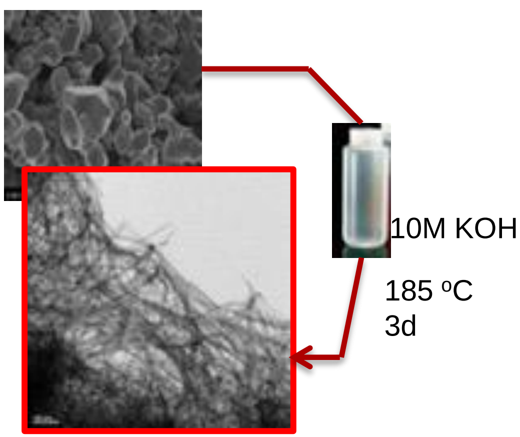
2012

2013

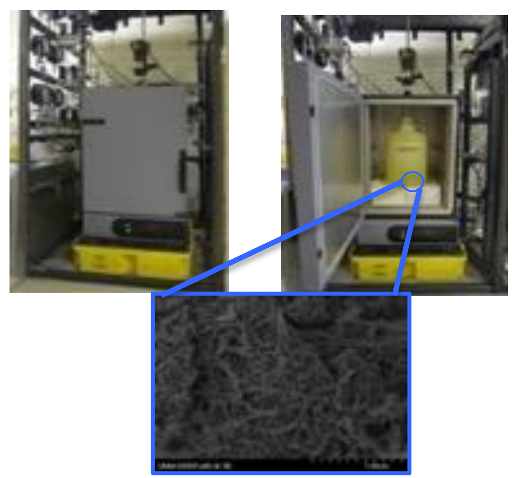
2014

2015

2016



Nanofillers developed



5 kg prep developed

Testing of Flywheel

Benefits to all involved are anticipated for the Carleton/Cobham, PowerThru, and Sandia collaboration (including OE and Zyvex).

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Albuquerque, New Mexico

Sandia
- Lab scale idea implemented
- Product viability stepping-stone for larger grid-based flywheel systems

Westminster, Maryland

Carleton/Cobham
- Develops a process for winding nano-loaded materials
- New job potential as C/C may assume overseas manufacturing

OE-DOE
- Tech Transfer: TRL 1 to ~7
- Improved flywheels increase reliable electricity for grid
- New jobs

POWERTHRU Clean Flywheel Energy Storage

Livonia, Michigan

PowerThru
- Comparative analysis of flywheel produced w/ different resin system
- Improved flywheels
- Improved commercial and defense related UPS product

Columbus, Ohio

Zyvex
- New customer base
- Novel nanofillers (not CNT)
- New composite materials

Woburn, Massachusetts

Barbour Stockwell Inc.
- New customer base
- New composite materials

★ 3-way NDA in place

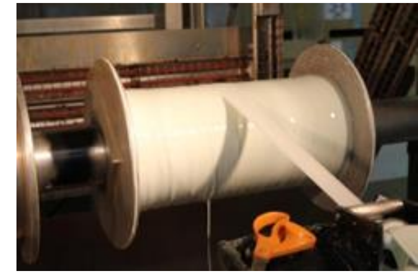
Sandia's Project Status:

+ Contract with PowerThru finalized
+ flywheels 'qualified: degassing and balancing assembly; low-high speed cyclic testing (27-52 Krpm).

+ four flywheels built and tested
  - EPON-A
    - EPON-A with TiO2 nanofillers
  - EPON-B
    - EPON-B with graphene nanofillers

+ Supplied a used PowerThru flywheel for comparison

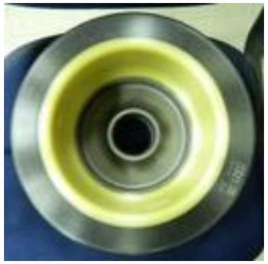
+ Materials testing at Sandia initiated
  - non-destructive
  - destructive

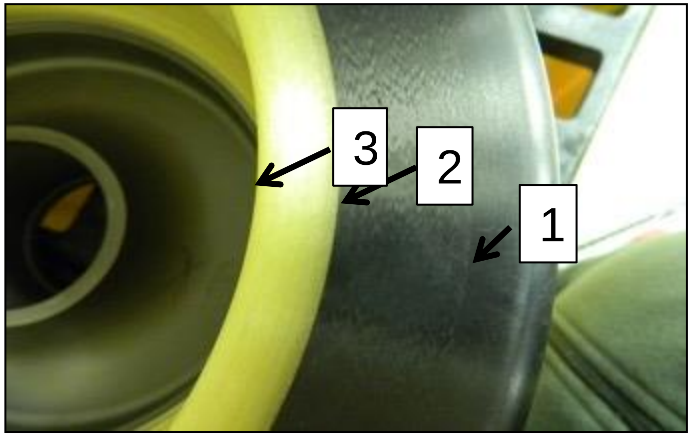



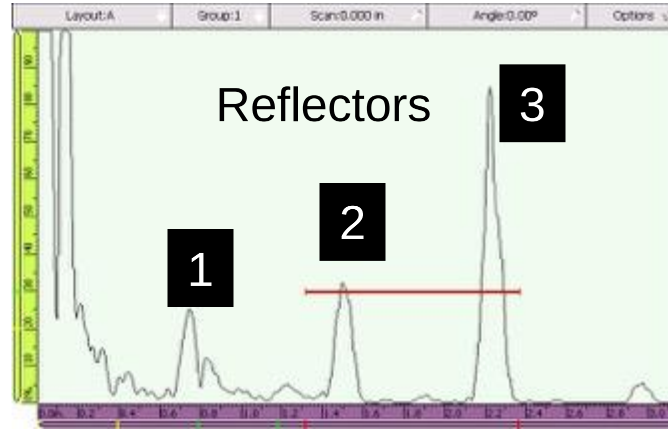




Non-destructive Preliminary Inspection



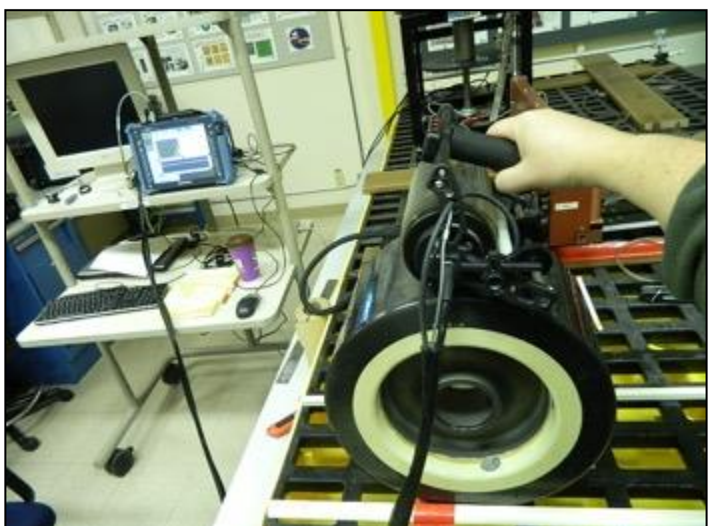




Thickness ~ 1.95-2.22”
Velocity ~.1160 in/µs

A-Scan signal as shown on the thickest area. All areas were clean signals.

Ultrasonic Phased Array Test 1 MHz GE Wheel

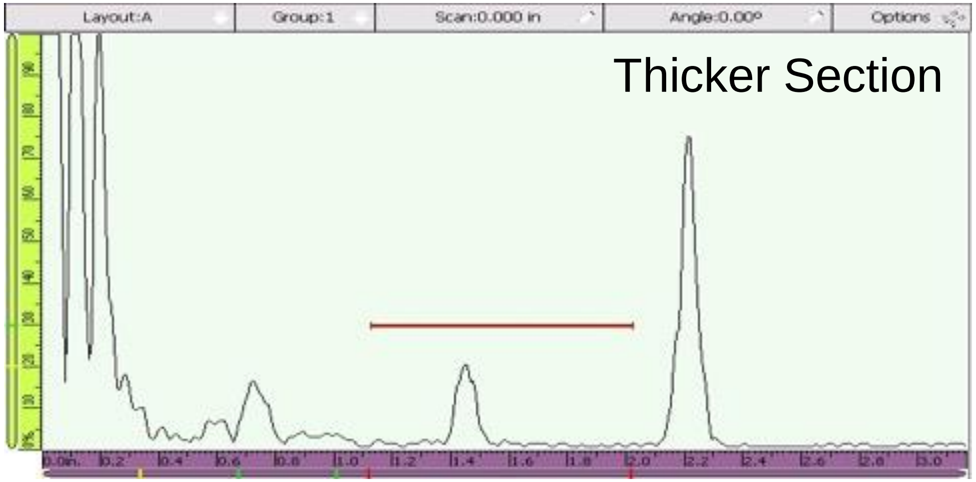


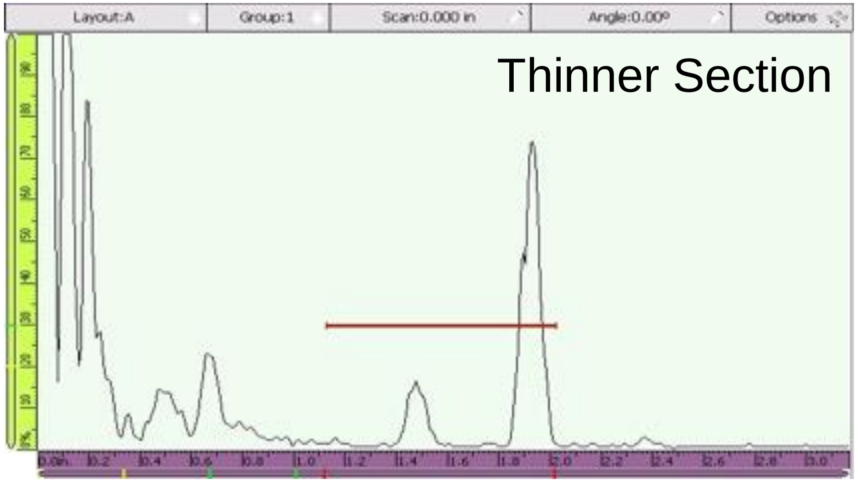
NOTE: Each Scan Was 3.8” in Width.

Typical A-Scan Signal on all three flywheels

- Ultrasonic Contact Test 1 MHz/1.0” Diameter Transducer

Part was scanned on a lazy Susan wheel indexed down the part ½ of the transducer diameter

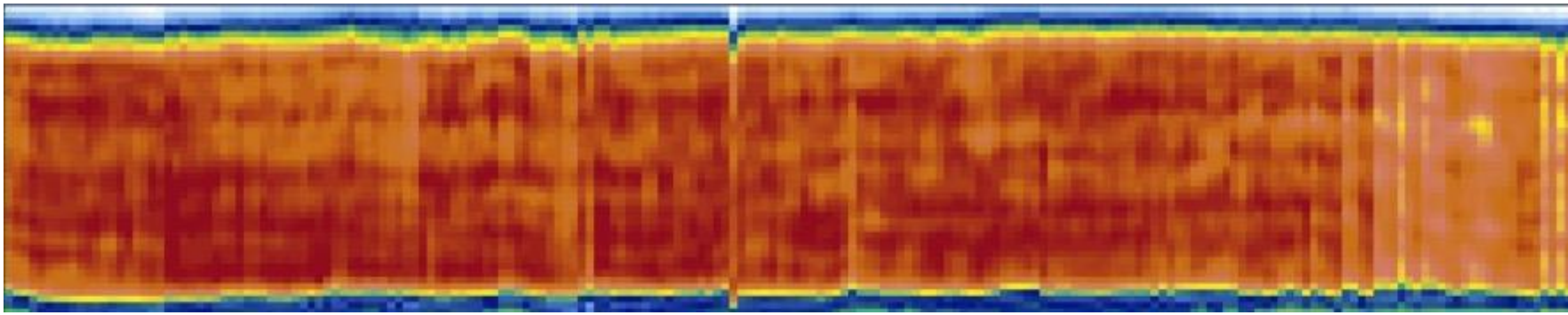




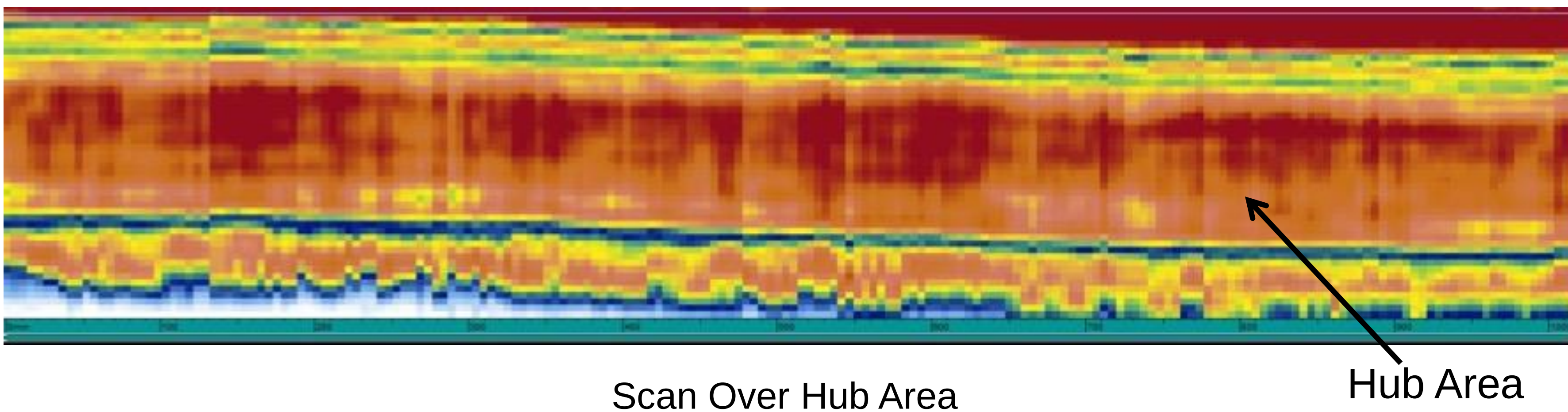
<u>Note</u>: A-Scan signals on all three parts appeared clean with very low noise. No Part gave any signal shifts or indications of porosity clusters or delamination signal shifts

PowerThru Wheel- Phased Array MHz

GE Wheel Probe C-Scans



Carbon/Fiberglass Only



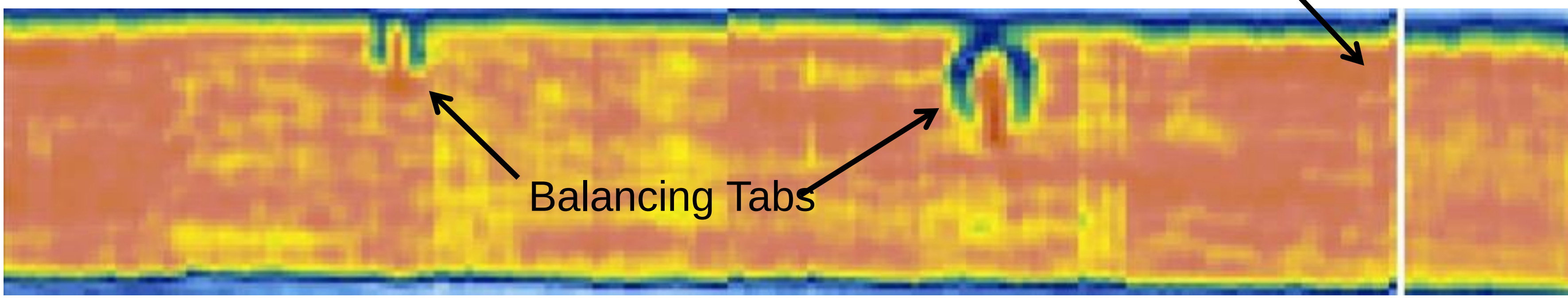
Scan Over Hub Area

Part appeared very clean. Scanning over the hub area caused a loss in signal strength, so gain was increased in order to see the signal.

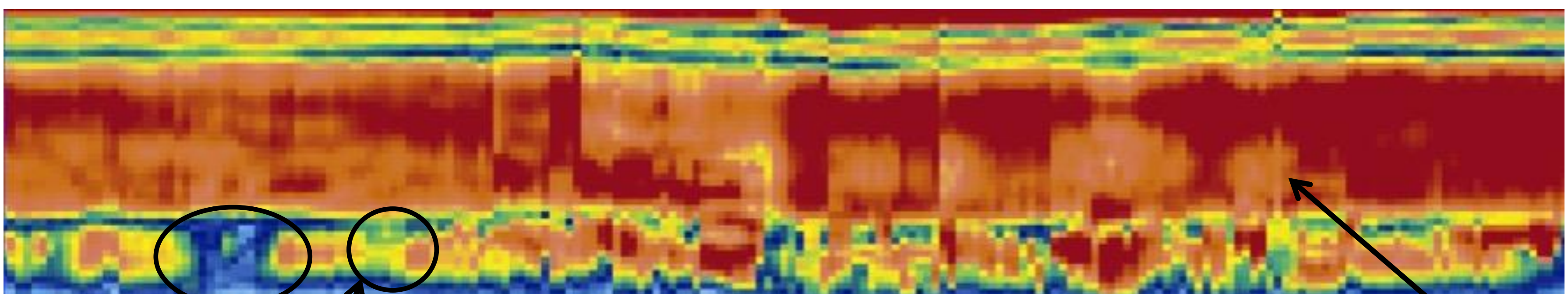
EPON A blank Flywheel:
Phased Array MHz GE Wheel Probe C-Scans

Balancing Tabs

Data Line Drop- Not Due to Part



Very Clean Scan- No defect indications noted.



Balancing Tabs

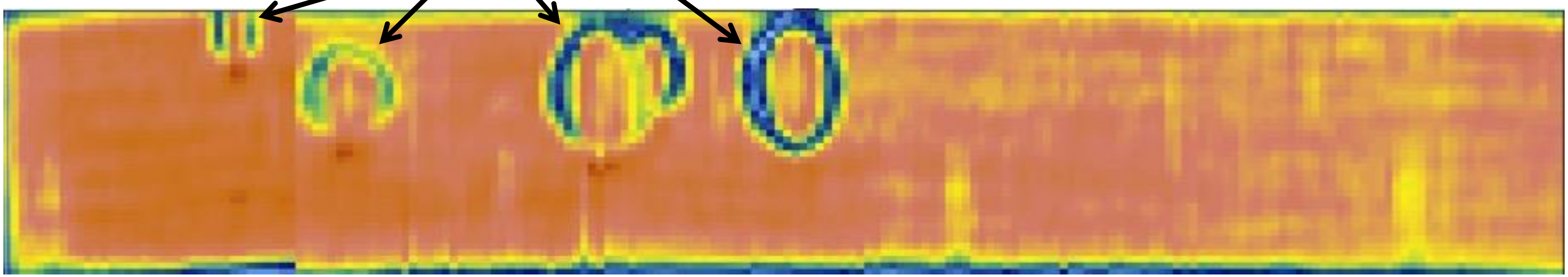
Scan Over Hub Area

Hub Area

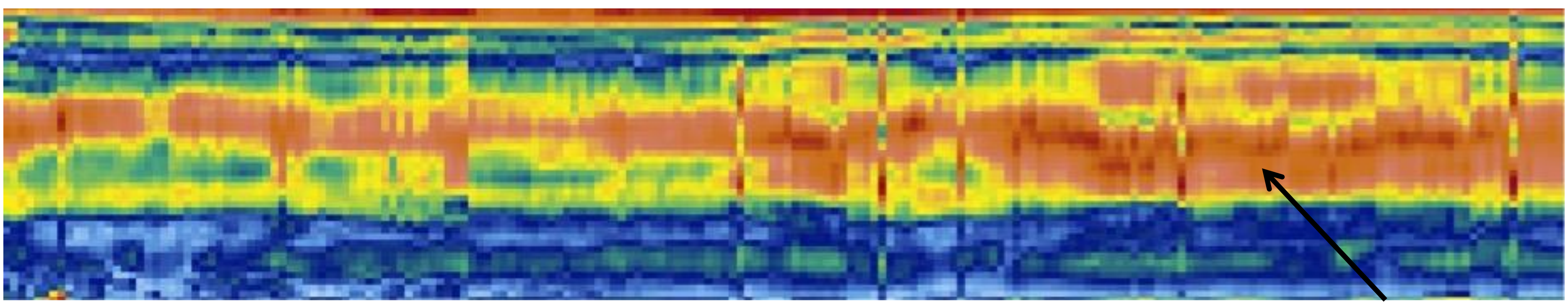
EPON A TiO_2 Flywheel:

Phased Array MHz GE Wheel Probe C-Scans

Balancing Tabs



Very Clean Scan- No defect indications noted.



Scan Over Hub Area

Hub Area

This particular hub area had a decrease in amplitude signal when compared to the other two parts. Due to a variance in resin systems or bond line between the hub and the fiberglass.

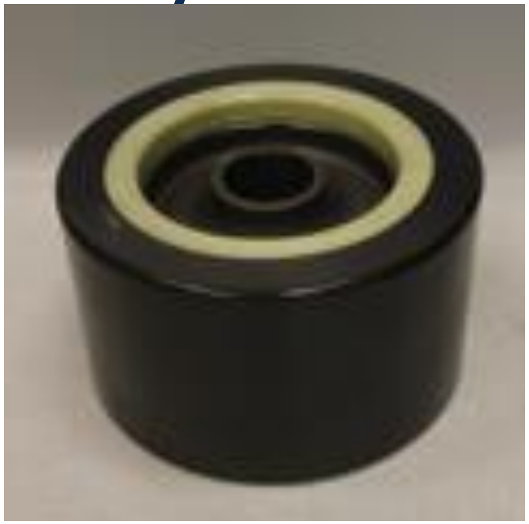
Ultrasound Flywheel Summary

- The balancing tabs (thin spots of adhesive) were clearly detected on the innermost back wall surfaces. This indicates good flaw detection sensitivity and no gross flaws were detected.
- It was more difficult to pick up the tabs next to the hub because the GE wheel probe had to hang partly off of the part during the inspection.

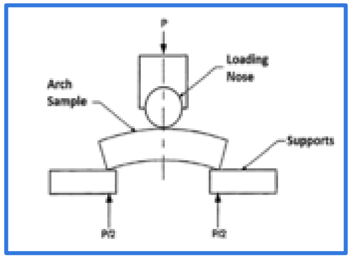
- The *PowerThru Carbon* wheel was initially inspected as a baseline inspection. After setting up on this particular part, the other two flywheels were inspected.
  - *EPON A-blank* showed clear signal and was very similar when compared to the PowerThru wheel.
  - *EPON A-TiO_2* had a decrease in signal amplitude over the hub area when compared to the other two flywheels. When compared to the other two flywheels the gain setting was increased by ~3dB to attain the same level of back wall amplitude using both the single element and rolling wheel.

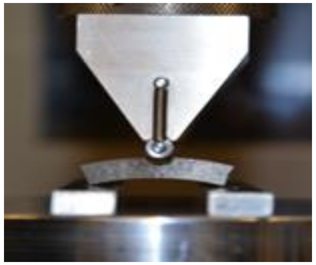
- No concentrated pockets of porosity were noted and the material appeared very clean.
- No indications were identified that would indicate delaminations in the laminate or disbonding from the hub in any of the flywheels.

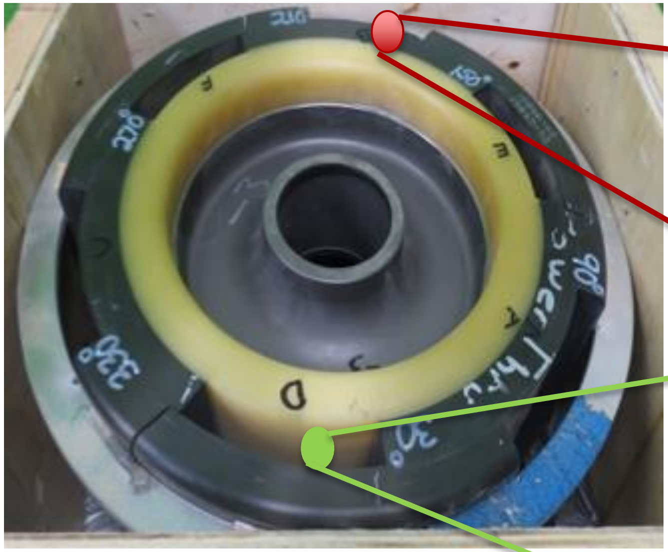
Flywheel dissection



- Used PowerThru flywheel, Blank flywheel and TiO_2 filled flywheel were dissected.
- audible 'pop' occurred upon initial cuts
- flywheel material was water jet cut and then machined into coupons for mechanical testing.

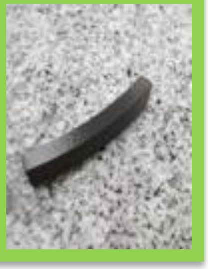






- Blank flywheel sections flaked apart.

a TiO_2 nanofilled flywheel sections held together.



Summary/Conclusions

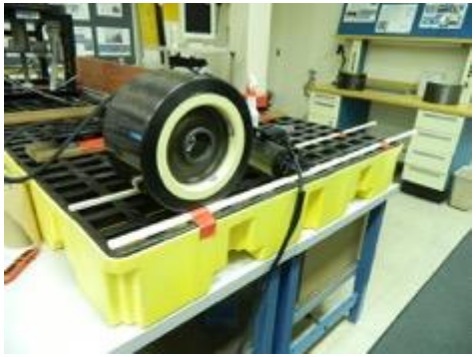
Milestones:

+ Flywheels have been built: commercial, blank, TiO_2 filled.

+ Initial Ultrasound testing revealed little detectable differences.

+ Material testing (ILSS, fiber fraction, particle dispersion) selected over burst testing (Barbour Stockwell, Inc)

+ Differences noted.



- No concentrated pockets of porosity were noted and the material appeared very clean. No indications were identified that would indicate delaminations in the laminate or disbonding from the hub in any of the flywheels.

- Commercial, blanks, and filled tested.
- Initial results indicated they behave differently
- Results on testing pending.

Future Tasks: Milestones for FY 16

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Milestones:

+ Finialize testing to determine impact of naonfillers on working component.

+ Finalize dog-bone testing (MSU) to undestand nanofiller impact on test samples and compare to working component

+ Fundamental study of shape, functionalization, and composition (graphene (sheets), Al_2O_3 (sheets), CNF (wires) and TiO_2 (wires) of nanofillers on dogbone.

+ Establish new commercial interactions: Duracell and Lockheed Martin have expressed interest in some preliminary discussion

LOCKHEED MARTIN

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